

Multiple Scattering of Sound by Internal Waves and Acoustic Characterization of Internal Wave Fields in Deep and Shallow Water

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LONG-TERM GOALS

- To improve understanding of the effects of internal waves (IW) on sound propagation underwater.
- To develop an empirical statistical description of IWs in shallow water.
- To measure acoustically path-averaged energy of IWs in the ocean and variations of the energy on time scales from hours to years.
- To develop a comprehensive model of the IW spectra in the deep ocean and their regional and temporal variability.

OBJECTIVES

1. To extend the existing theory of 3-D and 4-D acoustic effects induced by IWs to the regime of strong sound scattering.
2. To model the frequency shift and spectrum broadening of CW sound scattered by spatially-diffuse, random IWs in deep and shallow water.
3. To develop a predictive model of the acoustic frequency evolution at sound scattering by a train of tidally-generated, nonlinear IWs in a coastal ocean.
4. To assess the feasibility of inverting a measured frequency spectrum of the sound emitted by a narrow-band source, for spatially-averaged parameters of the IW fields in shallow and deep water.

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5. To develop a theoretical description and a computer model of the average acoustic field in a deep ocean in the presence of a statistical ensemble of IWs.
6. To perform numerical simulations of the inversion of the mean acoustic field for IW characteristics and determine optimal parameters of the corresponding field experiment.

APPROACH

Three complementary representations of the acoustic field are used in this work, namely, the ray-theoretical description of the field, full-wave representation of the field in the normal-mode basis, and the parabolic approximation.

A simple, convenient, and computationally efficient description of forward sound scattering by 3-D inhomogeneous, time-dependent sound speed fluctuations can be obtained by using the ray perturbation theory (Godin et al., 2006). The theory accounts for the change in geometry of 4-D (i.e., space-time) rays due to small fluctuations in the sound speed, and allows one to express first- and second-order perturbations in travel time, arrival angles, pressure amplitude, and other acoustic observables as integrals of weighted environmental perturbations calculated along unperturbed rays. When IW-induced sound speed variations are viewed as random fluctuations superimposed on a deterministic background, the theory expresses statistical moments of acoustic observables in terms of integrals of appropriate statistical moments of environmental perturbations. The integrals are calculated along unperturbed rays. Predictions of the analytical theory will be verified against Monte Carlo simulations of sound propagation.

For a full-wave analytic description of 3-D and 4-D acoustic effects in the strong perturbation regime, where the spatial displacements of acoustic trajectories due to IW-induced perturbations are comparable to or larger than the correlation length of the environmental perturbations, we use Chernov's "local method" in conjunction with the Markov approximation. This allows us to evaluate second moments of the acoustic field. With this technique, only smallness of scattering over the correlation radius of the inhomogeneities is required. This condition is fulfilled for practical situations and for frequencies on the order of a hundred Hertz, however it can be violated at higher frequencies. In this case, standard diagrammatic technique can be used for calculation of the average field. This approach requires fluctuations of the index of refraction to be Gaussian, which is a good approximation in many practical situations. The equation for the average acoustic field in the statistically homogeneous in horizontal plane stratified waveguide satisfies an integral-differential equation. The kernel of the integral operator is calculated as a power series in the standard deviation of the refraction index. In the lowest order (Burrer approximation), the kernel is proportional to the spectrum of fluctuations. This equation also determines specific "average field" modes which generally can be different from the standard acoustic modes.

The key individuals that has been involved in this work are Oleg A. Godin (CIRES/Univ. of Colorado and NOAA/ESRL), Alexander G. Voronovich and Valery U. Zavorotny (NOAA/ESRL), and Robert L. Weber (STC and NOAA/ESRL). Dr. Voronovich has been primarily responsible for developing full-wave theoretical descriptions of multiple scattering of sound by internal gravity waves. Drs. Zavorotny and Weber have been involved in numerical simulations of the acoustic field and contributed their expertise on waves in random media. Dr. Godin took the lead in the theory and modeling of the 3-D and 4-D effects in underwater sound propagation.

WORK COMPLETED

Limitations of acoustic characterization of IW fields using surface-reflected arrivals have been addressed. Statistics of rapid variations in the travel time and amplitude of surface-reflected arrivals due to 3-D sea surface roughness have been quantified (Fuks, Charnotskii, and Godin, 2006).

A novel passive acoustic remote sensing technique has been studied theoretically which can potentially be applied to measure IW-induced sound speed perturbations as well as IW-induced currents. The technique relies on long-range correlations of diffuse acoustic fields to retrieve the acoustic Green's function from the two-point correlation function of ambient noise in the ocean. Assuming that the noise is generated by delta-correlated random sources distributed on a surface, it has been shown that a measurement of the two-point correlation function of noise allows one to quantify the flow-induced acoustic nonreciprocity and determine the travel times of waves propagating in opposite directions, which are normally obtained in reciprocal transmission experiments employing acoustic transceivers located at the two points (Godin, 2006c). It has been also established, that the deterministic time-domain Green's function of an arbitrarily inhomogeneous, moving or motionless, dissipative fluid can be found as the second derivative in time of the two-point correlation function of acoustic noise when the noise field is generated by random volume sources, density of which is proportional to the local value of dissipation (Godin, 2006h). In particular, this relation between the Green's function and the two-point correlation function of ambient noise holds in the case of thermal noise. Thermal noise dominates in the ambient noise in the ocean at frequencies above 50-200 kHz, depending on the sea state (Mellen, 1952).

Accuracy of modeling the interaction of low-frequency underwater sound with the ocean surface when using the pressure-release boundary model and/or ray-theoretical concepts has been investigated. Comparison of the simplified models with a consistent full-wave treatment of sound reflection at and transmission through a flat water-air interface as well as of sound scattering at the rough interface, showed that the simplified models do not correctly reproduce the sound field when a point sound source is located at a depth smaller than acoustic wavelength. Most of the acoustic energy emitted by a sound source located at a depth of a fraction of the wavelength is radiated into air (Godin, 2006d). The counter-intuitive behavior of the acoustic energy flux is explained by a combination of the Lloyd's mirror effect, which is a consequence of the strong density contrast of the two media, and the vertical energy flux associated with inhomogeneous (evanescent) plane waves emitted by the source. Non-zero vertical energy flux in a superposition of incident and surface-reflected inhomogeneous plane waves is a consequence of the sound speed in air being smaller than the sound speed in water (Godin, 2006g).

The role of ocean bottom stratification, its shear rigidity, and sea floor roughness in sound scattering and mode coupling in shallow water has been investigated (Godin, 2006e, 2006f). An efficient perturbation technique has been developed to describe sound scattering in fluid-solid waveguide. It has been demonstrated that shear rigidity of marine sediments qualitatively changes characteristics of sound transmission between points in deep and shallow water, compared to the previously studied case of fluid bottom (Pierce, 1983), when ocean depth at source or receiver locations is smaller than the cut-off depth of the first acoustic normal mode.

RESULTS

Fluctuations of a bearing angle ψ in a fixed source-receiver geometry is a measure of IW-induced horizontal refraction. Correlation of the bearing fluctuations of a ray arrival at two receivers can be calculated as follows:

$$\left\langle \psi \left(x_R + \frac{\Delta x_R}{2}, \frac{\Delta y_R}{2}, z_R + \frac{\Delta z_R}{2} \right) \psi \left(x_R - \frac{\Delta x_R}{2}, -\frac{\Delta y_R}{2}, z_R - \frac{\Delta z_R}{2} \right) \right\rangle = \frac{2c^2(x_R, z_R)}{q^2(x_R) \cos^2 \chi(x_R)} \times \int_{x_S}^{x_R} A_0 \left(\chi(x), b(x), \Delta y_R \frac{q(x)}{q(x_R)}; \mathbf{r}_0(x) \right) \frac{q^2(x)}{\cos \chi(x)} dx, \quad (1)$$

where angular brackets denote ensemble average, x and y are range and cross-range horizontal coordinates, z is the vertical coordinate, and integration is along an perturbed eigenray between a source at $(x_S, 0, z_S)$ and the mid-point $(x_R, 0, z_R)$ between two receivers. Equation (1) has been derived using the ray perturbation theory (Godin et al., 2006). Here $c = \langle C \rangle$, C and χ are sound speed and grazing angle on the eigenray,

$$b = \left[\Delta z_R - \tan \chi(x_R; x_R, z_R) \Delta x_R \right] \frac{p(x, \chi_0)}{p(x_R, \chi_0)}, \quad q(x; x_R, z_R) = \int_{x_S}^x \frac{c(x', z_0(x'; x_R, z_R)) dx'}{\cos \chi(x'; x_R, z_R)}, \quad (2)$$

$$A_0(\chi, b, y; \mathbf{r}) = \frac{-1}{2 \cos \chi} \int_{-\infty}^{+\infty} \frac{\partial^2 w}{\partial y^2}(x, y, b + x \tan \chi; \mathbf{r}) dx, \quad (3)$$

$p(x, \chi_0) = (\partial z_0 / \partial \chi_0)_x$, $\chi_0 = \chi(x_R)$ is the launch angle of the eigenray, and w is the correlation function of fluctuations in sound slowness:

$$\left\langle \left[C^{-1}(\mathbf{r}_1, t_1) - c^{-1}(\mathbf{r}_1) \right] \left[C^{-1}(\mathbf{r}_2, t_2) - c^{-1}(\mathbf{r}_2) \right] \right\rangle = w \left(\mathbf{r}_1 - \mathbf{r}_2, t_1 - t_2; \frac{\mathbf{r}_1 + \mathbf{r}_2}{2}, \frac{t_1 + t_2}{2} \right). \quad (4)$$

The function A_0 has a meaning of the acoustically-relevant integral characteristic of environmental fluctuations. Expressions similar to Eqs. (1) - (3) have been also obtained for correlation of azimuthal arriving angles at different geophysical times.

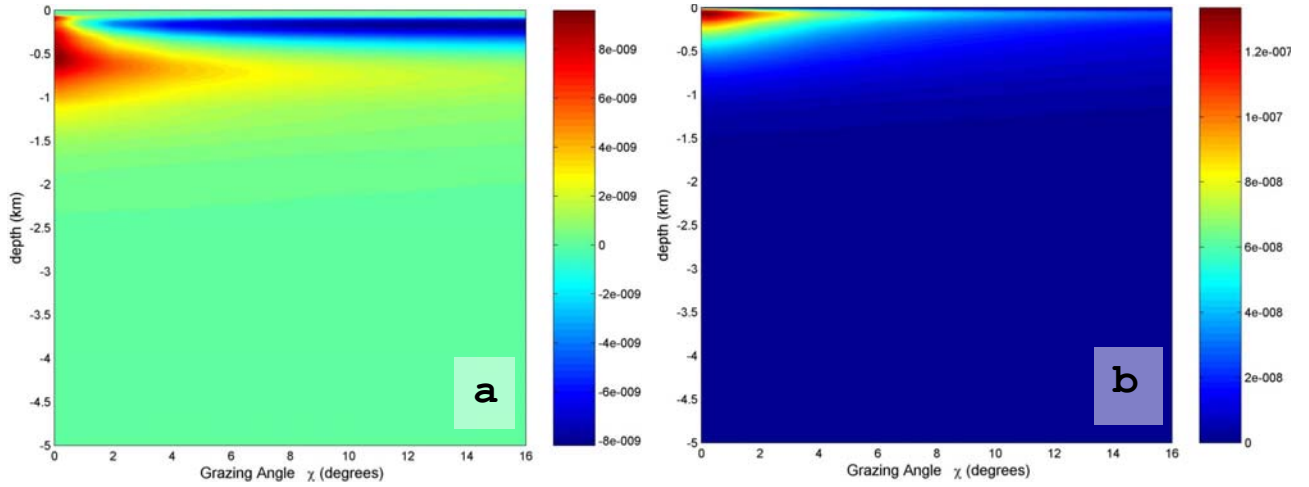


Figure 1. Dependence of an acoustically relevant integral characteristic, $A_0(\chi, b, y; z)$ [$\text{sec}^2 \text{ km}^{-3}$], of the internal-wave induced cross-range sound-speed gradients, on depth z and grazing angle χ at $y = 0$, $b = 100 \text{ m}$ (a) and $y = 100 \text{ m}$, $b = 0$ (b). Internal wave field is described statistically by the Garrett-Munk spectrum assuming an exponential buoyancy profile.

[When $b = 0$, A_0 is positive and decreases when grazing angle decreases. When $b = 100 \text{ m}$, A_0 takes both positive and negative values; dependence on the angle and depth is non-monotone. On both panels, A_0 has a significant magnitude only above 1500 m, with maxima located above 600 m.]

For IW-induced sound speed fluctuations, the function A_0 has been calculated using a rigorous implementation of the Garrett-Munk spectrum in terms of modes of the internal waves. Highly structured dependence of A_0 on its arguments is illustrated in Figure 1. Large tables of A_0 in 4-D space of its arguments have been generated to enable an efficient calculation of correlations of acoustic observables.

A systematic numerical study is on-going of the two-point correlation function of azimuthal arrival angles and its dependence on the launch angle of an eigenray, source-receiver geometry, background sound speed profile, and spectral content of the IW field. Highly anisotropic nature of the correlation function has been established; correlation radii with respect to the receiver separation in depth and cross-range are typically much smaller than correlation radius with respect to the receiver separation in range. An example of the correlation dependence on the launch angle of a ray and the cross-range

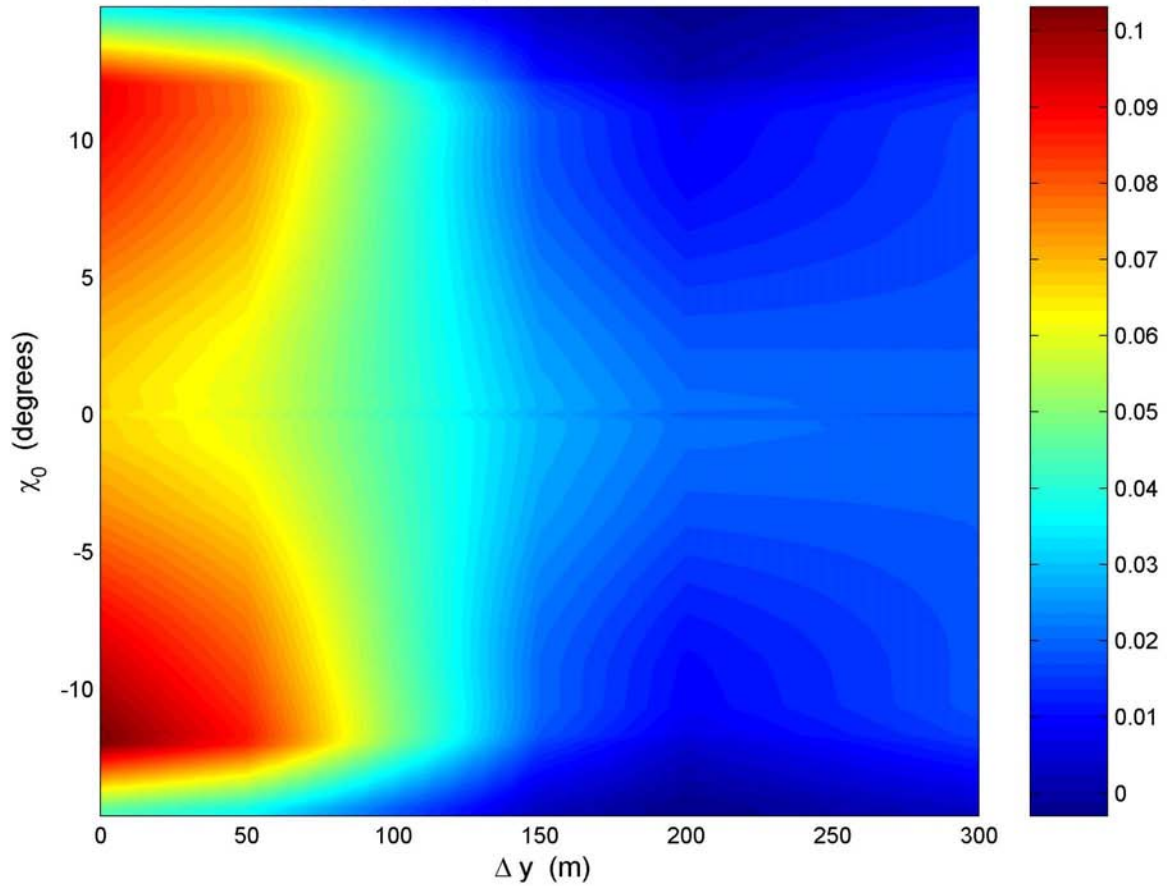


Figure 2. Correlation of bearing angle fluctuations at points $(x_R, \Delta y/2, z_R)$ and $(x_R, -\Delta y/2, z_R)$ at sound propagation in the ocean with a canonical sound speed profile and internal waves with the Garrett-Munk spectrum. Source and receiver are on the axis of the canonical sound speed profile. Propagation range is 1 Mm.
[The correlation function is shown for ray launch angles from -15° to 15° and cross-range horizontal separation Δy of receivers from 0 to 300 m. On the figure, the correlation varies between zero and 0.13. The correlation generally decreases as Δy increases. The highest values of correlation are seen for $\Delta y < 50$ m and launch angles around 11° .]

separation of receivers is shown in Figure 2. Preliminary results indicate that, for sources and receivers near the SOFAR channel axis, correlation radii are significantly larger for shallow than steep refracted rays. The difference is particularly pronounced for receiver separations in range. For propagation range of 1 Mm, sound source and receivers near the axis of the canonical sound speed profile, and IWs with the Garrett-Munk spectrum, the correlation radii vary between 35 m and 140 m for depth separation and 70 m and 95 m for cross-range separation, depending on the launch angle of a refracted ray.

IMPACT/APPLICATIONS

Knowledge of the correlation time and correlation radii of bearing fluctuations and of the dependence of the radii on source-receiver geometry allows one to evaluate the feasibility of acoustic monitoring

and devise an observation scheme to characterize IW fields in the ocean and their variability in geotime using measurements of acoustic fluctuations caused by random horizontal refraction.

RELATED PROJECTS

Low-frequency, long-range sound propagation through a fluctuating ocean: Analysis and theoretical interpretation of existing and future NPAL experimental data (N00014-04-IP2-0009.)

REFERENCES

O. A. Godin, V. U. Zavorotny, A. G. Voronovich, and V. V. Goncharov, Refraction of sound in a horizontally-inhomogeneous, time-dependent ocean, *IEEE J. Oceanic Engineering*, **31**, No. 2 (2006)

R. H. Mellen, The thermal-noise limit in the detection of underwater acoustic signals, *J. Acoust. Soc. Am.* **24**, 478-480 (1952)

A. D. Pierce, Augmented adiabatic mode theory for upslope propagation from a point source in variable-depth shallow water overlying a fluid bottom, *J. Acoust. Soc. Am.* **74**, p. 1837-1847 (1983)

PUBLICATIONS

I. M. Fuks, M. Charnotskii, and O. A. Godin, Statistics of the travel time and intensity of the two first arrivals of short pulses backscattered by a rough 3-D surface, *Waves in Random and Complex Media* (2006) [in press, refereed]

O. A. Godin, Calculation of amplitudes of acoustic normal modes from the reciprocity principle, *J. Acoust. Soc. Am.* **119**, No. 4, p. 2096-2100 (2006a) [published, refereed]

O. A. Godin, L. M. Brekhovskikh and the theory of wave propagation in layered media. Calculation of mode amplitudes from the reciprocity principle. In: *Ocean Acoustics. Proceedings of the 11th L. M. Brekhovskikh's Conference* (GEOS, Moscow, 2006b), p. 64-69 [published]

O. A. Godin, Recovering the acoustic Green's function from ambient noise cross-correlation in an inhomogeneous moving medium, *Phys. Rev. Lett.* **97**, No. 5, 054301 (2006c) [published, refereed]

O. A. Godin, Anomalous transparency of water-air interface for low-frequency sound, *Phys. Rev. Lett.* (2006d) [in press, refereed]

O. A. Godin, Surface-to-volume wave conversion in shallow water with a gently sloping bottom, *Acoust. Phys.* (2006e)

O. A. Godin, Surface-to-volume wave conversion in shallow water with a corrugated bottom, *Acoust. Phys.* (2006f)

O. A. Godin, Transmission of low-frequency sound from water to air, *Acoust. Phys.* (2006g)

O. A. Godin, Emergence of the acoustic Green's function from thermal noise, *J. Acoust. Soc. Am.* (2006h)

O. A. Godin and K. A. Naugolnykh, Guided propagation of naturally occurring infrasound in troposphere and stratosphere, *Geophys. Research Lett.* **32**, No. 23, L23824 (2005) [published, refereed]

O. A. Godin and D. R. Palmer (Editors), *History of Russian Underwater Acoustics* (World Scientific, Singapore, 2006) [in press]

O. A. Godin and A. G. Voronovich, Fermat's principle for dispersive waves in nonstationary media. In: *Proceedings of the International Seminar Days on Diffraction 2005* (Saint Petersburg, Russia, June 28 - July 1, 2005) (St. Petersburg Univ., 2005), p. 109-115 [published]